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THEORETICAL OPERATING RANGES AND CALIBRATION RESULTS OF THE ARL TWENTY-INCH HYPERSONIC WIND TUNNEL

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D. L. BROWN
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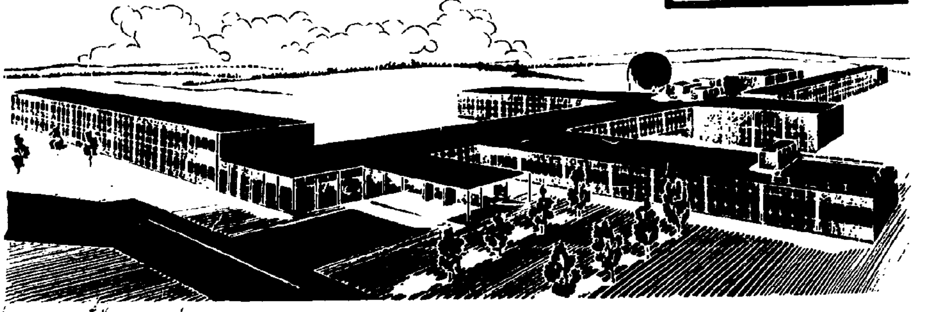
OCTOBER 1963

AEROSPACE RESEARCH LABORATORIES
OFFICE OF AEROSPACE RESEARCH
UNITED STATES AIR FORCE



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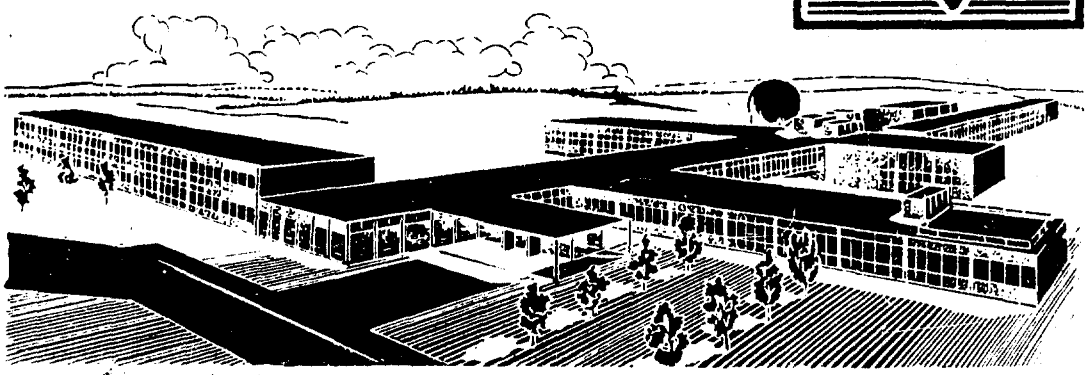

NOTICES

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Contract AF 33(616)-8453
Proj~~ect~~ 7064

AEROSPACE RESEARCH LABORATORIES
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UNITED STATES AIR FORCE
WRIGHT-PATTERSON AIR FORCE BASE, OHIO

FOREWORD

This interim technical report was prepared by the University of Cincinnati Hypersonic Aerodynamics Research Staff on Contract AF 33(616)8453, titled "Experimental Aerothermodynamic Investigations", for the Aerospace Research Laboratories, Office of Aerospace Research, United States Air Force. The work reported herein was accomplished under Project 7064, "Aerothermodynamic Investigations in High-Speed Flow" during the period between February of 1962 and June of 1963. Colonel Andrew Boreske, Jr., Deputy Commander of the Aerospace Research Laboratories, served as project monitor for this work.

ABSTRACT

Results of calibration tests conducted in the ARL 20 in. ~~twenty-inch~~ hypersonic wind tunnel are presented. ~~in this interim technical report.~~ Included ~~in these tests~~ are total pressure surveys, total temperature surveys, and blockage tests of various model configurations. All tests were conducted with the nominal Mach 14 throat installed in the tunnel. The total temperature survey was carried out in a direction normal to the flow at a fixed axial station, with the total pressure survey being conducted in the normal direction also, but at various axial locations. The models used in the blockage tests included hemisphere cylinders of various sizes and a 20° included-angle cone.

The range of flow parameters which may be simulated were computed from the predicted operating limits of the tunnel and are presented in graphical form. These graphs include the range of pressure, temperature, density, and Reynolds number possible in the HTS-14.

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I INTRODUCTION

The twenty-inch hypersonic wind tunnel at the Aerospace Research Laboratories, henceforth referred to as the HTS-14, is an axisymmetric free jet facility designed to operate at Mach numbers from 8 to 14 over a wide range of free stream Reynold's numbers. The HTS-14 is a "blow-down" type facility employing a set of vacuum pumps and a vacuum sphere on the low pressure side and compressed bottled air (to 3000 psia) on the high pressure side. A schematic diagram of the facility is illustrated in Figure 1, while Figure 2 is a photograph of the tunnel area.

The duration of the "blow-down" is limited by the capabilities of the vacuum pumps and the vacuum sphere. Pressure in the vacuum sphere increases throughout the "blow-down", with the run being terminated when the back pressure increases beyond the allowable value necessary to maintain that particular Mach number flow.

A "run" consists of two modes of operation, which are basically the bypass and the normal modes of operation. During the bypass or stabilization mode, air is exhausted from the heater through a water cooled auxiliary nozzle to the atmosphere. This phase of operation allows the total pressure and total temperature to stabilize at the pre-set values. When stabilization has occurred, the tunnel is put into the normal mode of operation. In this mode, the air flow is directed through the test nozzle and into the test section where the model being tested is located. The air is then exhausted into the vacuum system.

The facility is designed to operate at a maximum stagnation pressure of 2500 psia and a minimum stagnation pressure of 400 psia. The maximum total temperature allowable is 2800° R, which may occur at a maximum air flow of 2.6 pounds per second and at a maximum electrical input to the heater of 1800 KW.

Calibration information obtained in the above mentioned tunnel with the Mach 14 throat installed is presented herein. Total pressure data, total temperature data, and blockage data were obtained in these calibration tests. Also included in this report is the theoretical range of operating conditions of the HTS-14.

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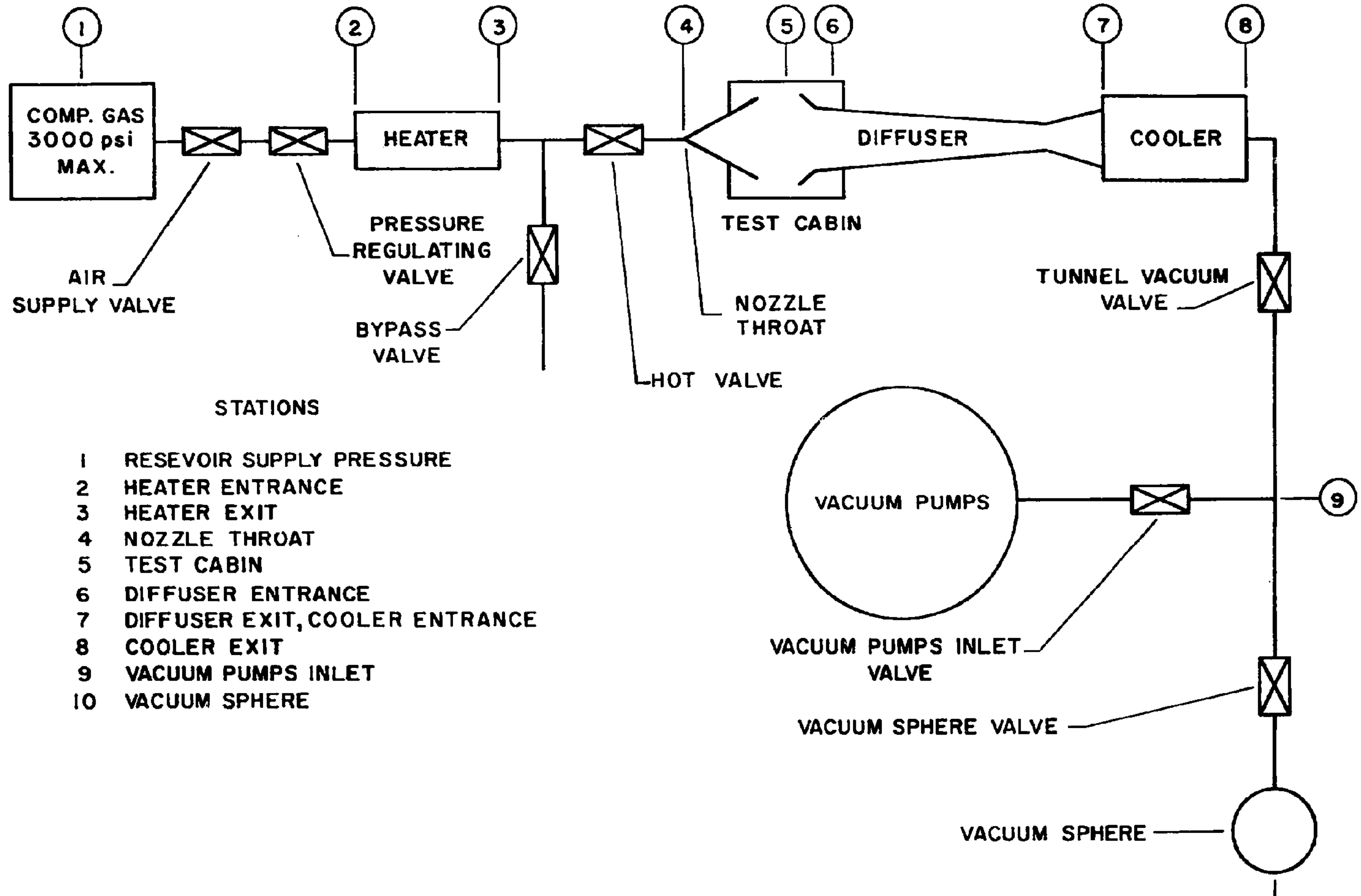


FIGURE 1 - SCHEMATIC DIAGRAM OF HTS-14

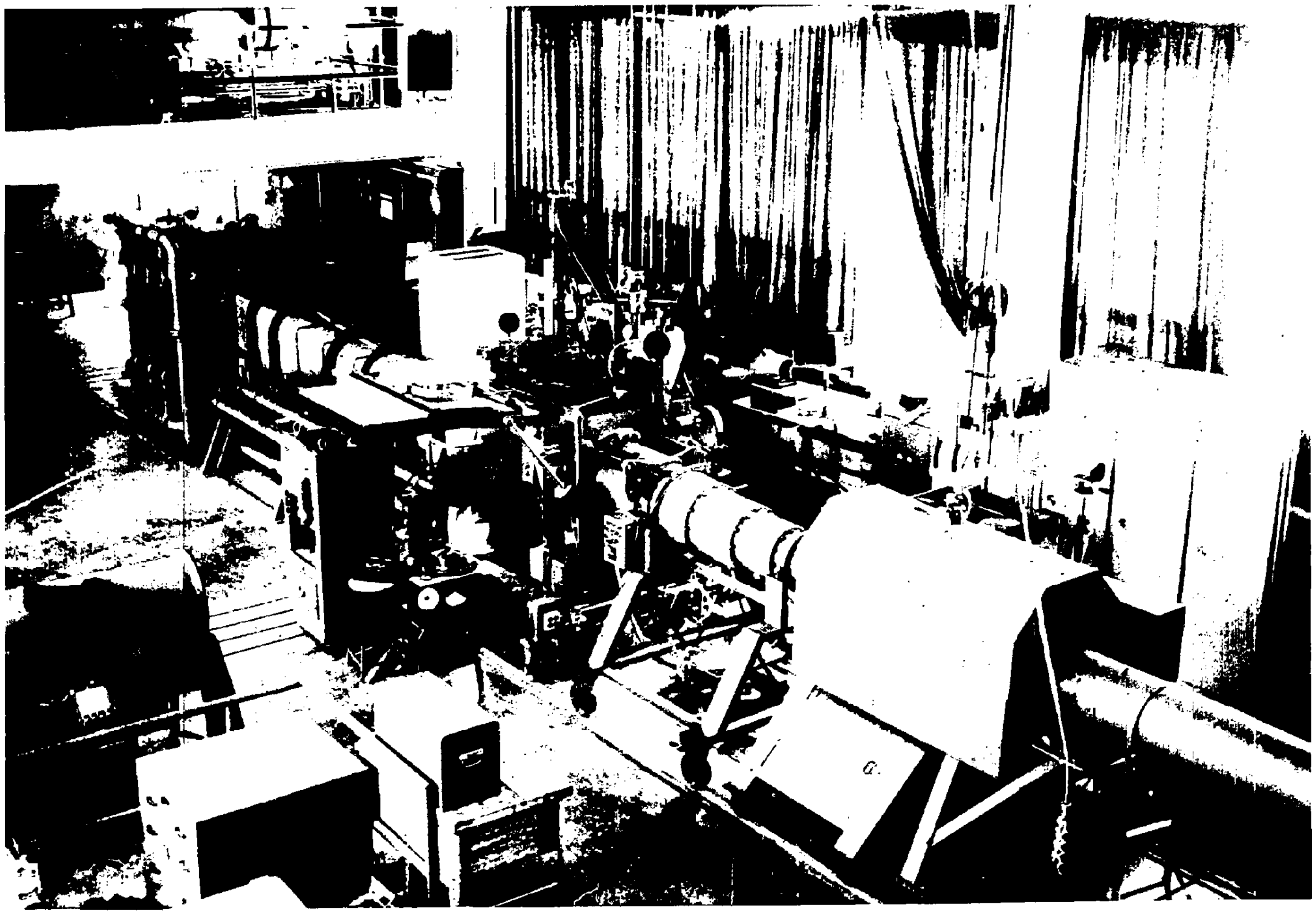


FIGURE 2-EXTERIOR VIEW OF HTS-14

II DESCRIPTION OF FACILITY

A basic description of the main components of the HTS-14 is given here primarily to aid the reader in gaining a complete understanding of the facility, its operation, and its limitations. A more detailed description of the HTS-14 and its components along with their design characteristics and initial operational tests, may be found in References 1 and 2.

HIGH PRESSURE AIR SUPPLY SYSTEM

The high pressure air is furnished from externally located high pressure air bottles, which are periodically replenished by air compressors located in the pump-house portion of the facility. The air supply is controlled by a Jamesburg ball-valve which is actuated from the main control console. This supply valve is remotely operated by actuation of a solenoid valve to supply air to the proper end of the pneumatic cylinder. Microswitches sense the open and closed positions of the valve and illuminate the proper indicator lights on the main control console. The air supply system also contains a manually controlled shut-off valve located near the storage reservoir. This valve is designed to be used to shut off the air supply to the high pressure piping during periods of maintenance on the ball-valve and/or control valve. As a precautionary measure the air supply valve closes automatically if the console power is shut off.

The stagnation pressure is controlled by a fully pneumatic system which is operated from the main control console. This control valve is located upstream of the heater so that switchover of the control point is not required when the mode of operation is changed.

The stagnation pressure is recorded in two sections, the heater exit and the test nozzle inlet. This allows the pressure to be controlled and recorded in the bypass mode of operation, and by use of the pressure transmitter located in the nozzle inlet, gives a more accurate measurement of the total pressure when the tunnel is in the normal mode of operation.

The pressure pickup in the heater is connected to a 0-3000 psig pressure transmitter which furnishes a corresponding 3-15 psig signal to the controller. The stagnation pressure as measured in this location is read out on a 0-3000 psig Taylor pressure gauge.

The pressure in the nozzle inlet is recorded on the chart contained in the pressure controller. Greater resolution of the stagnation pressure as recorded at the nozzle inlet is obtained by using three pressure transmitters to divide the total range into three subranges. These ranges are 400-800, 700-1500, and 1400-3000 psig; each of which gives full range recorder action. The desired range is controlled by a stagnation pressure selector contained on the main control console.

AIR HEATER

The heater system is composed of five separate and individually controllable sections. These heater sections house the heater elements which are made of Kanthal A-1 wire. The air is heated when it passes over the wire elements which are energized by electrical power. The heater elements are rated for continuous service at a maximum wire temperature of 2462° F. The melting point of the wire elements is 2750° F. However as a safety precaution, the wire temperature should be held below 2300° F., thus eliminating the possibility of hot spots in the wire exceeding the melting temperature.

Stagnation temperature is controlled, indicated, and recorded from control points located just downstream of the heater outlet. It is also indicated and recorded from a thermocouple located in the stilling chamber, which is located upstream of the test nozzle inlet. As mentioned previously, five heater sections compose the heater. Sections 1, 2, 3, and 4 are either "on" or "off", and are controlled through selector switches on the main control console. The current input to section 5 is controlled by means of a controller-recorder, a Westinghouse Furnation electronic control unit, and three saturable core reactors. The desired temperature is set on the temperature controller-recorder, and when this pre-set temperature is reached, the electronic control unit regulates the power input to the heater elements in section 5 to maintain a constant temperature.

The heater selection switches on the main control console, which is shown in Figure 3, energize the circuits when they are placed in the "on" position. In addition, when the switch for section 5 is turned on, it energizes the motor-generator set and the Furnation. However, the power to the heater elements is not turned on until the Heater Power Master Switch is depressed. In addition, the Heater Power Master Switch must be depressed whenever a new heater section is added to or taken out of the flow.

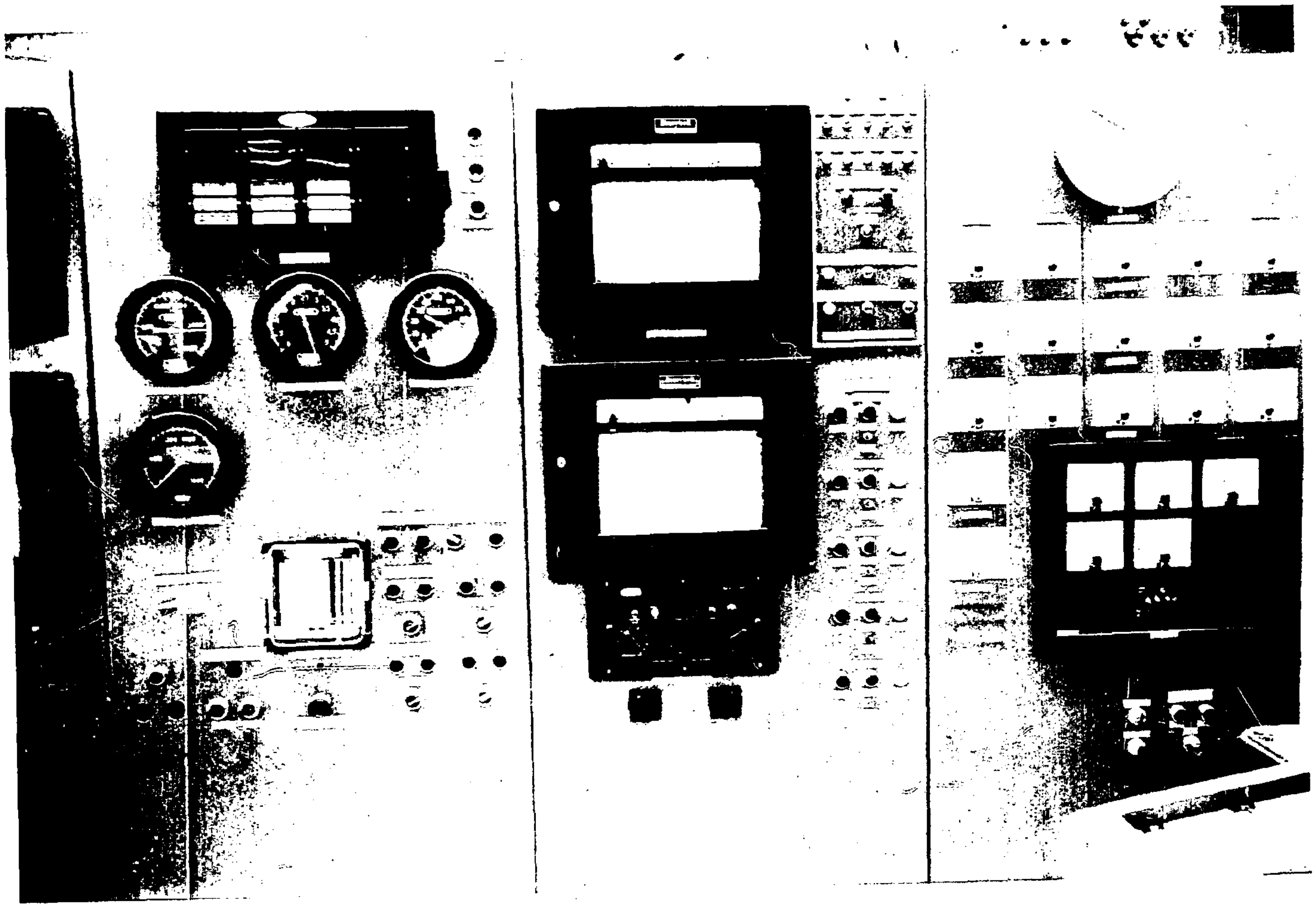


FIGURE 3 - MAIN CONTROL CONSOLE FOR HTS-14

As a safety measure, the heater section can not be energized unless the heater is pressurized above the setting of the heater pressure switch. This pressure switch senses air pressure in the heater and is interlocked with the heater master control. Since the bypass system cannot dead-end the heater, heater air pressure insures air flow thru the heater to provide cooling for the heater elements. This heater pressure switch also cuts off all power to the heater elements if the pressure in the heater should ever fall below the pre-set valve. In addition, air flow through the heater cannot be started unless the output of the pressure controller to the stagnation pressure control valve is reduced to zero. The valve is then to be gradually opened manually. This procedure prevents an initial strong blast of air from passing through the heater and possibly damaging the heater elements.

Thermocouples are also installed in the heater to sense the temperature of the inner shell at two locations and as wire temperature pick-ups, one for each heater section.

BYPASS SYSTEM

The bypass system basically consists of the bypass valve, the "hot valve" and the exhaust nozzle. The "hot valve" and bypass valve are actuated by hydraulic cylinders under 1500 psi pressure. The cylinders are interlocked so that as one cylinder is closing its valve, the exhaust fluid is supplied to the other cylinder to open its valve; and vice versa.

The outlet of the bypass tee houses the exhaust nozzle. This is sized to provide the same sized throat as the test nozzle, and thus simulate air flow requirements of the test nozzle during stabilization.

TEST SECTION

The test section, as shown in Figure 4, is essentially a steel box of 48 x 48 inch cross section which contains an electrically controlled model support system. The side walls are hinged at the top edge and are raised by means of hydraulic cylinders located on each side wall. In addition, the top of the test section has a removable plate for further access and for the mounting of additional model support systems.

The test cabin doors are positively locked in the extended position by means of latches on the cylinder heads. These must be manually released before retracting the pistons.

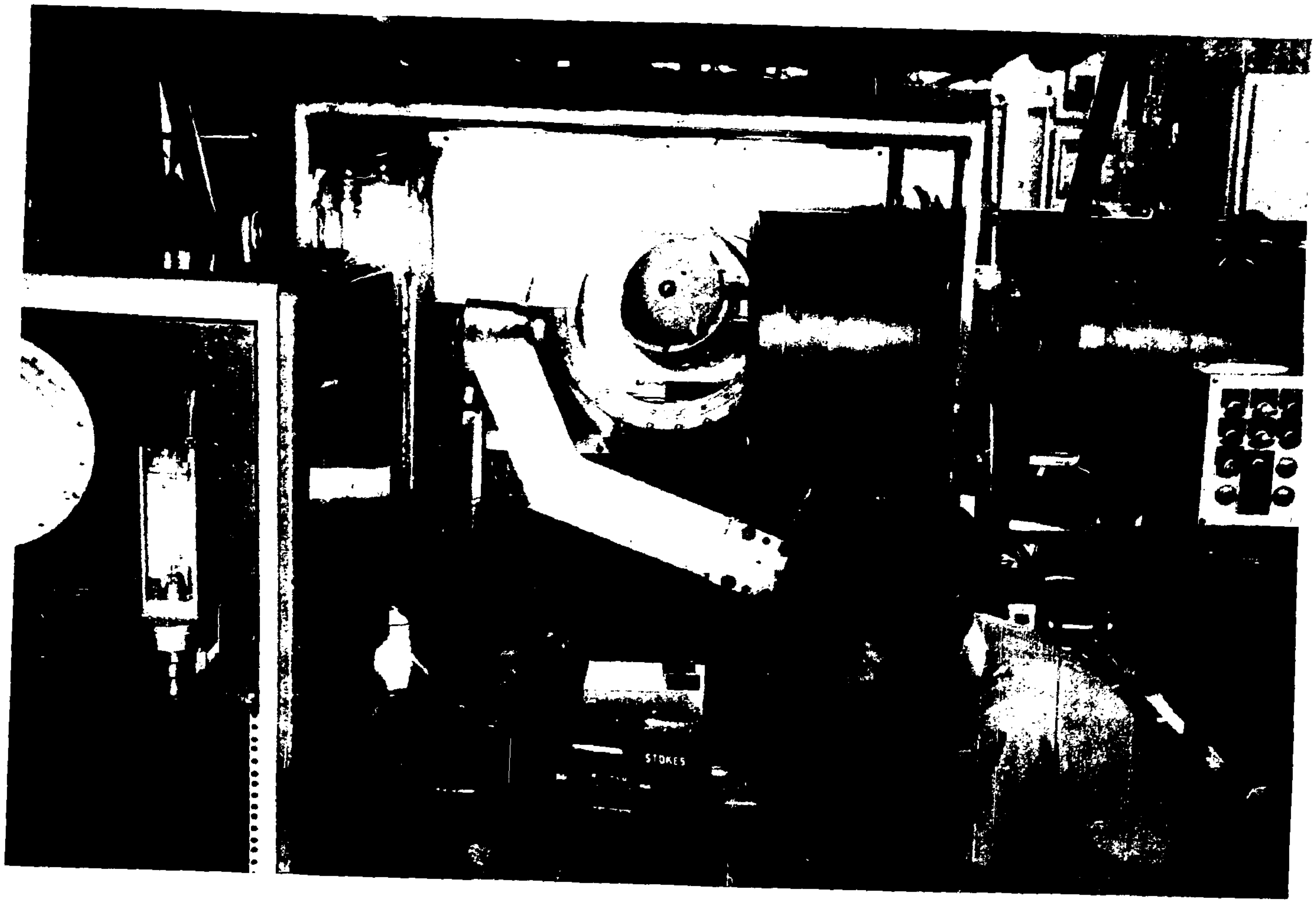


FIGURE 4-HTS-14 TEST SECTION

One micro-switch on each side is utilized to sense the side walls closed position and allow opening of the tunnel vacuum valve. This arrangement provides an interlock which prevents a vacuum from being introduced to the test section area unless both side walls are closed. The micro-switches are connected in series with the control for the tunnel vacuum valve, so that opening of the control circuit by either door being open, insures that the valve will close and remain closed until both doors are closed.

III RANGE OF TUNNEL OPERATING CONDITIONS

The operating range of a hypersonic wind tunnel, or more specifically, the ability of the tunnel to simulate certain flow properties, are most important when programming research in the tunnel. Thus, it was considered pertinent to determine the range of these various flow properties for the HTS-14.

Since the simulation properties depend only upon the final Mach number and the Reynolds number, with the latter being a function of the total conditions, the limits on total pressure and total temperature were first established. Figure 5 illustrates the total pressure and total temperature range of the HTS-14. The upper limits on both total pressure and total temperature were determined from the design limits of the tunnel, but no data existed on the lower limits of these parameters. Hence, they were determined using the procedure as described in the proceeding paragraphs.

The lower operational limit on total pressure for the HTS-14 was estimated from data in Reference 1 concerning the tunnel vacuum system and from actual operating experience gained during the calibration program. This was accomplished by cross plotting the vacuum sphere pressure after one minute of run time versus the total pressure, with the data for the graph being determined from Reference 1 plots of sphere pressure versus time during adiabatic filling of the sphere with the vacuum pumps in operation and plots of mass flow against total pressure for various tunnel Mach numbers. From operational experience, it was determined that the pressure at the diffuser exit is approximately 8 mm. of Hg higher than the sphere pressure. Hence, a graph of diffuser exit pressure versus total pressure was obtained by merely translating the sphere pressure axis in the above mentioned graph by 8 mm. of Hg. On the plot of diffuser exit pressure versus total pressure a second curve of recovered pressure versus total pressure was then plotted. This curve was obtained by assuming a diffuser efficiency of 90% and determining the recovered pressure at the diffuser exit for various total pressures using the aforementioned assumption of diffuser efficiency. The intersection of the two curves on this graph, therefore, defines the lowest total pressure at which the HTS-14 can operate for run times of one minute. The values predicted by this method agree reasonably well with the actual lower operating limits of total pressure at Mach 12 and 14, the Mach numbers at which actual tests have been accomplished thus far.

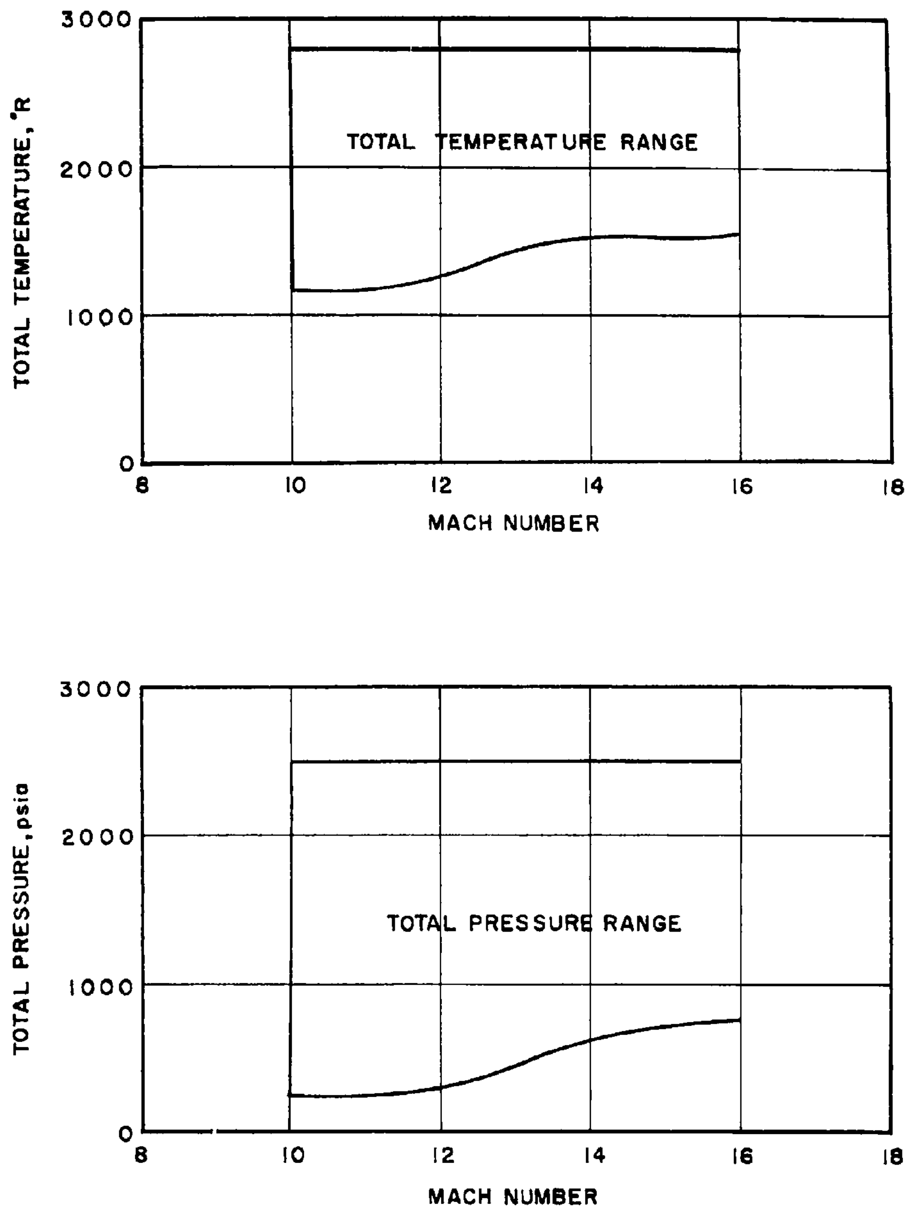


FIGURE 5-THEORETICAL OPERATING RANGES OF HTS-14

The lower limit on total temperature was obtained from the minimum temperature necessary to prevent liquefaction in the air stream. Since liquefaction is a function of free stream static pressure, this parameter was calculated from the lower total pressure limits as previously determined by using the isentropic flow tables and caloric imperfection correction factors of Reference 3. From the liquefaction data given by Reference 4, which included graphs of static temperature versus static pressure, the lowest static temperature possible to prevent liquefaction was found. The lower limit on total temperature was then determined by again using the tables and correction factors of Reference 3.

The dynamic pressure and the static pressure limits of the HTS-14 are presented in Figure 6, where the dynamic pressure limits were determined by using Reference 3.

Figure 7 illustrates the range of velocities and densities obtainable in the HTS-14. The density limits were calculated from Eq (1), the perfect gas relation, and a prior knowledge of the static pressure and temperature limits.

$$\rho = \frac{P}{RT} \tag{1}$$

where ρ = static density

P = static pressure

T = static temperature

R = gas constant

The velocity range was found from the static temperature range of the tunnel and the Mach number relation as expressed in Eq (2).

$$V = M\sqrt{\gamma RT} \tag{2}$$

where V = velocity

M = Mach number

γ = ratio of specific heats

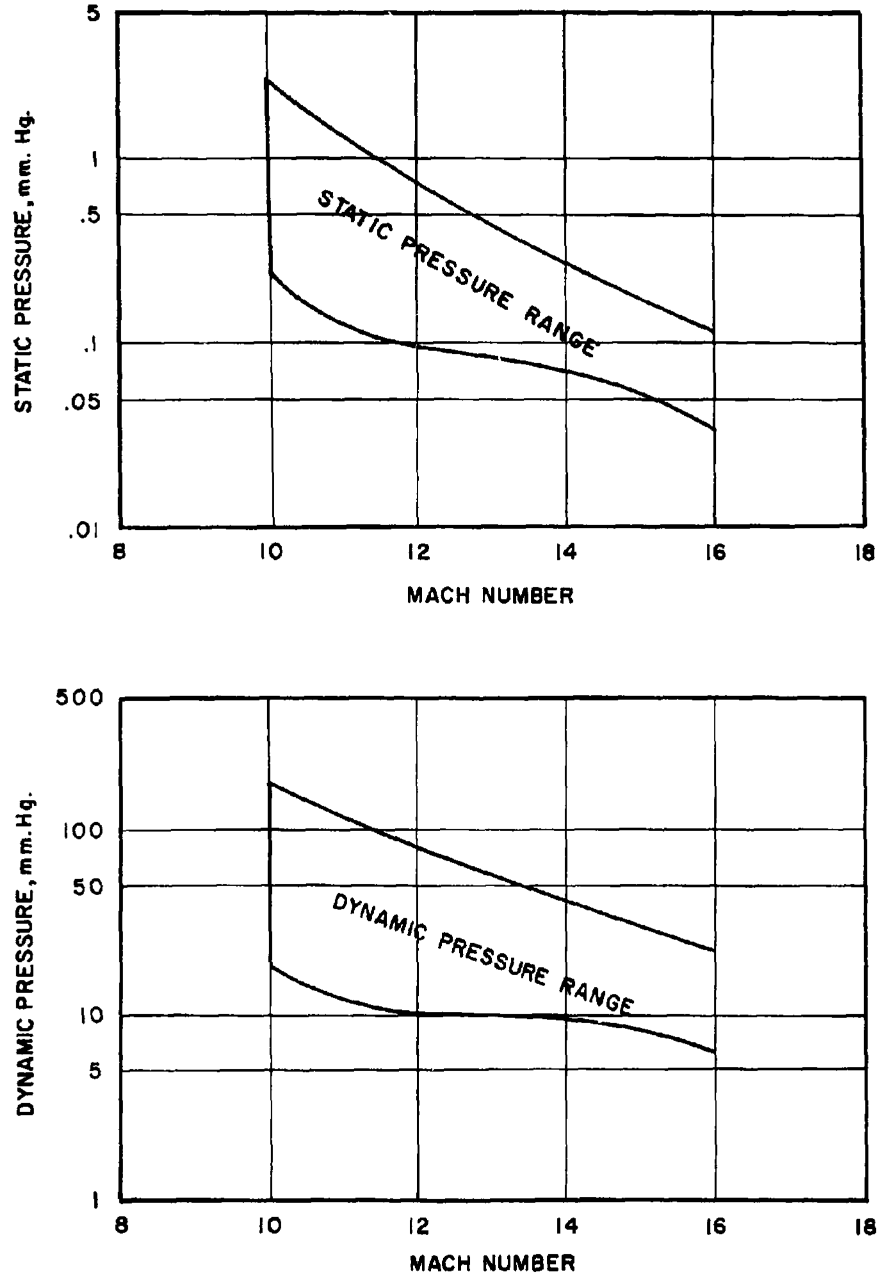


FIGURE 6 - THEORETICAL OPERATING RANGES OF HTS-14

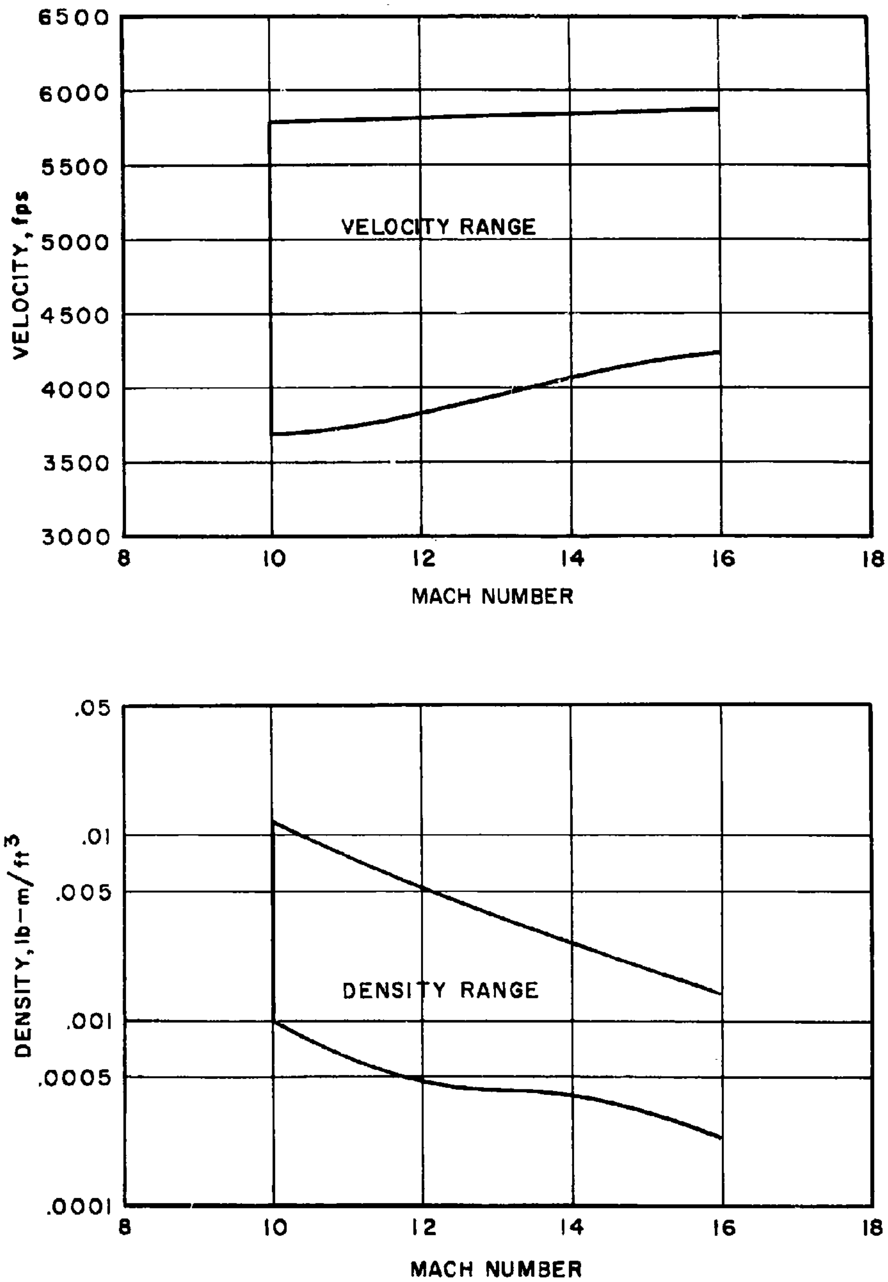


FIGURE 7 - THEORETICAL OPERATING RANGES OF HTS-14

The value of γ used in Eq (2) was determined from the static temperature for the particular Mach number and total conditions under consideration.

The free stream Reynolds number per foot for the range of parameters previously found is shown in Figure 8. The value of the Reynolds number per foot was found from

$$\frac{Re}{l} = \frac{\rho V}{\mu} \tag{3}$$

where μ, the viscosity, was determined by using Reference 5 for temperatures below 180° F and Reference 3 for temperatures above 180° F.

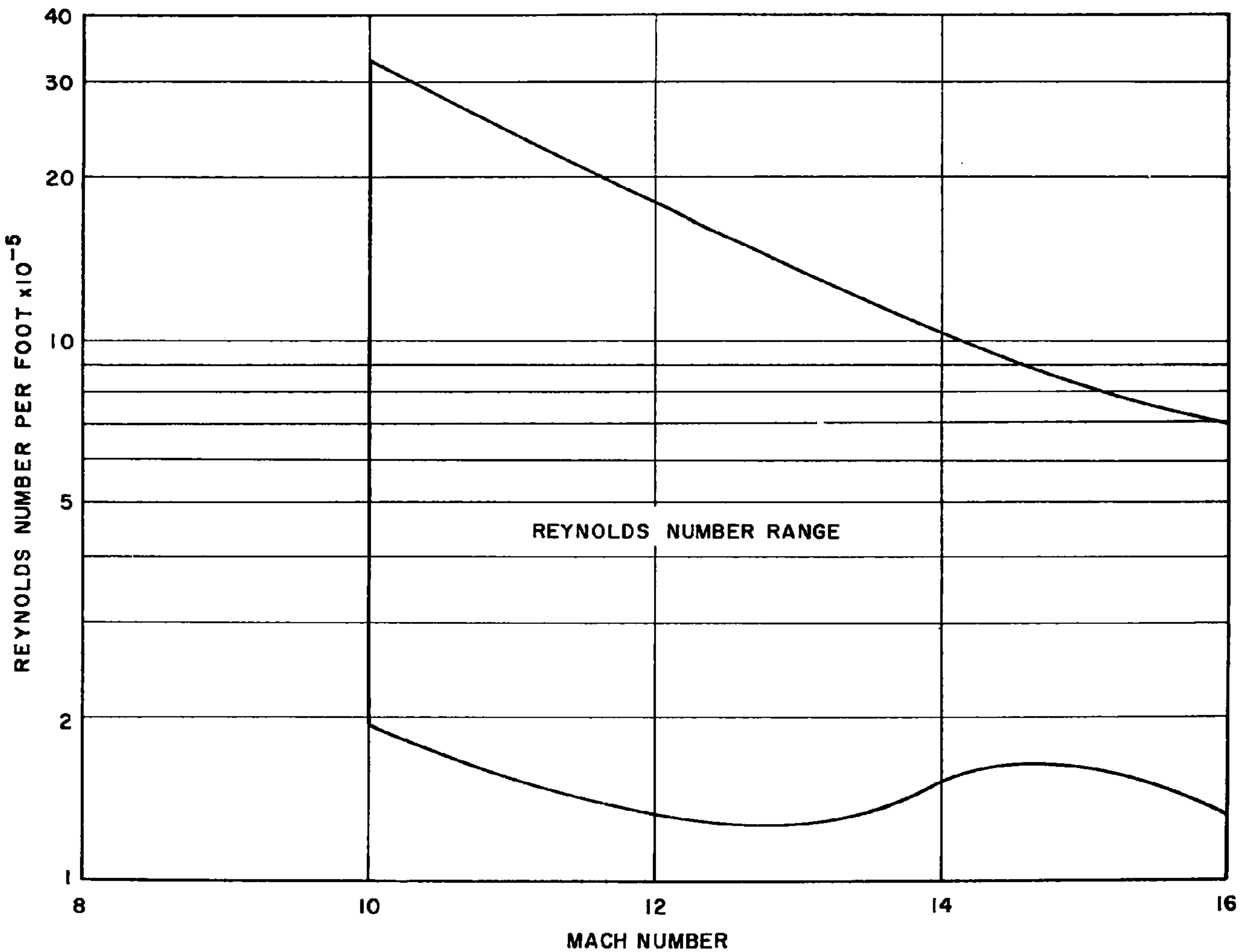


FIGURE 8 - THEORETICAL OPERATING RANGES OF HTS-14

IV CALIBRATION RESULTS

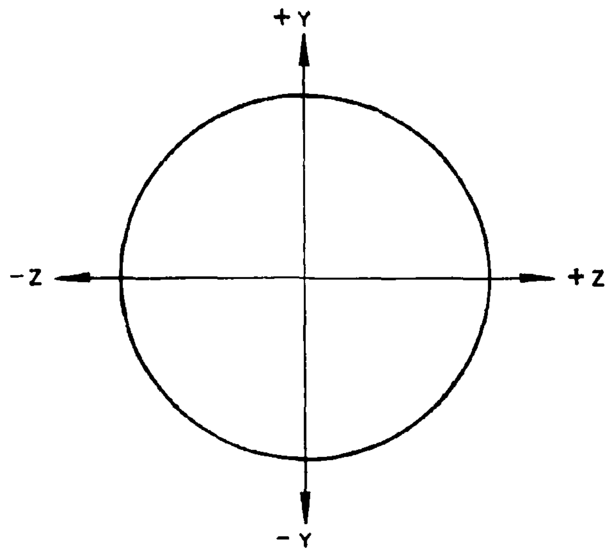
The calibration tests conducted in the HTS-14 by the U.C.H. A.R.S. consisted of a total pressure survey, a total temperature survey, and a tunnel blockage program. Two total pressure surveys are reported herein, as during the testing period two different throat sections were used. Although the throats were intended to be identical, there is a slight difference. Hence the pressure distribution in the core area of the flow is slightly different for the two throats. The total temperature survey and the blockage program were conducted with the initial throat section, henceforth referred to as throat #1.

PRESSURE SURVEY

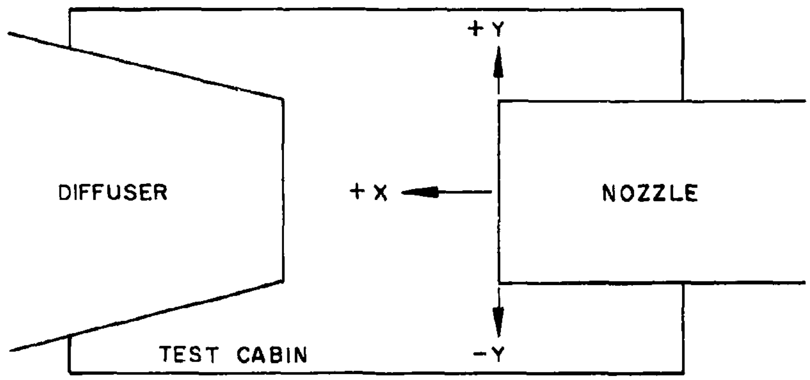
The total pressure survey of the HTS-14 included surveys in both the transverse and axial directions. The coordinate system assumed in these tests is shown in Figure 9, while a schematic diagram of the probe rake used is illustrated in Figure 10. Probes of various lengths were attached to this rake to achieve the desired axial locations.

The initial portion of the pressure survey was conducted without the use of the "hot valve". This was necessitated because at the time these tests were conducted, material problems prevented the use of an operational hot valve. Thus, stabilization of the air flow was accomplished by exhausting the air through the test section, which resulted in a rise of static temperature in the test cabin. This temperature rise occasionally limited the conditions of pressure and temperature at which tests could be successfully conducted, as the facility is equipped with an automatic device which cuts off all power being supplied to the tunnel if the temperature in the test cabin exceeds a pre-set maximum value. This temperature limit is necessary to protect the model support mechanism which is located within the test cabin. Since completion of the tests with throat #1, an operational hot valve has been developed and has performed most satisfactorily. All runs with throat #2 were accomplished with the use of the "hot valve".

The pressure data obtained in these tests was converted to Mach number by the standard procedure of assuming isentropic flow and correcting for caloric imperfections by use of Reference 3. Although all the runs conducted were not at the desired pressure settings of 700, 1000, 1300, or 1600 psia



VIEW DOWNSTREAM FROM NOZZLE



VIEW INTO TEST CABIN

FIGURE 9 -ASSUMED TUNNEL COORDINATE SYSTEM FOR CALIBRATION TESTS

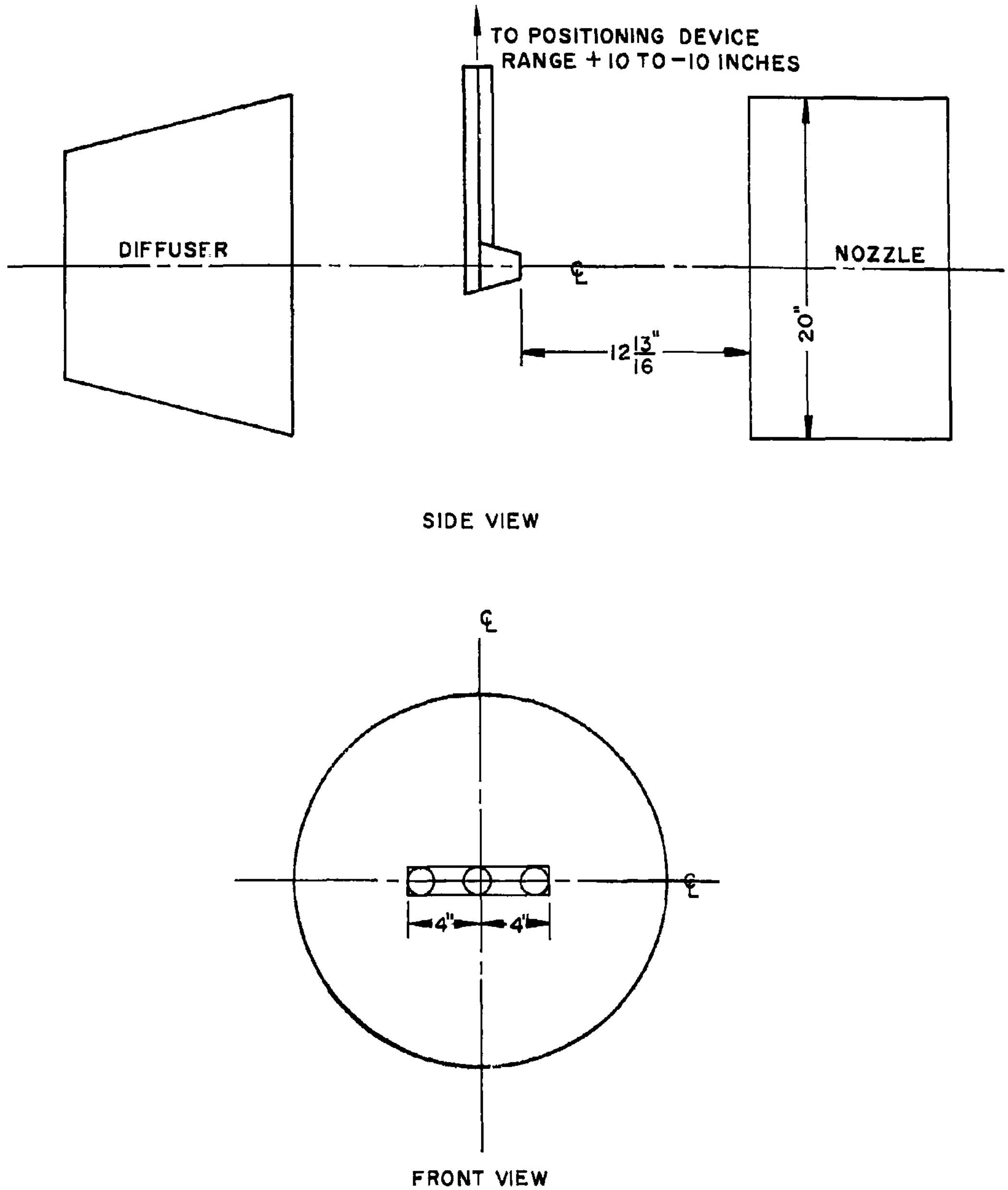


FIGURE 10–TOTAL PRESSURE CALIBRATION RAKE USED TO FIND MACH NUMBER DISTRIBUTION OF HTS-14

respectively, due to the inherent error in the pressure regulating valve, the runs were "normalized" to these pressures during the data reduction. This was accomplished by a cross plot of Mach number and stagnation pressure, and then assuming a linear interpolation to the desired pressure reading to obtain the "normalized" Mach number. Since the error in stagnation pressure was never greater than 4%, a linear interpolation was considered to be valid.

Instrumentation

The instrumentation used for the pressure survey consisted of three Statham model P6-5D-350 differential strain gauge transducers, a Consolidated Engineering Corporation Amplifier System, Model D, three Honeywell Model Electronik 17 strip chart recorders, and two Moseley Model 2D-2 X-Y plotters. The output of the three transducers was amplified and then fed into the three strip chart recorders, while two channels were recorded simultaneously on the X-Y plotter, both as a check on the recording equipment and as a means of recording the probe's vertical position. A Borg 1000 ohm Micropot Potentiometer, Model 205, with a linearity tolerance of 0.1% was used in conjunction with the X-Y plotter to record the vertical position of the probe.

The transducers were calibrated before and after each day of runs and were found to be linear within 0.2% and exhibited practically no zero shift between calibrations.

Results

Figures 11 thru 13 show the Mach number distribution in the vertical direction for both throat sections. As expected, the inviscid core of the flow is slightly smaller for higher total temperatures due to the increased boundary layer thickness. It should also be mentioned, however, that the runs at the higher total temperature were conducted without the hot valve. Hence, the nozzle temperature increased during the temperature stabilization, which, of course, would tend to thicken the boundary layer. It may be noted, by comparing Figure 11 with Figure 13, that the Mach number distribution is more symmetrical about the center-line with throat #1 than with throat #2.

Figures 14 thru 16 illustrate the Mach number distribution in the axial direction for both throat sections. As may be seen, throat #2 gives the smaller axial Mach number gradient.

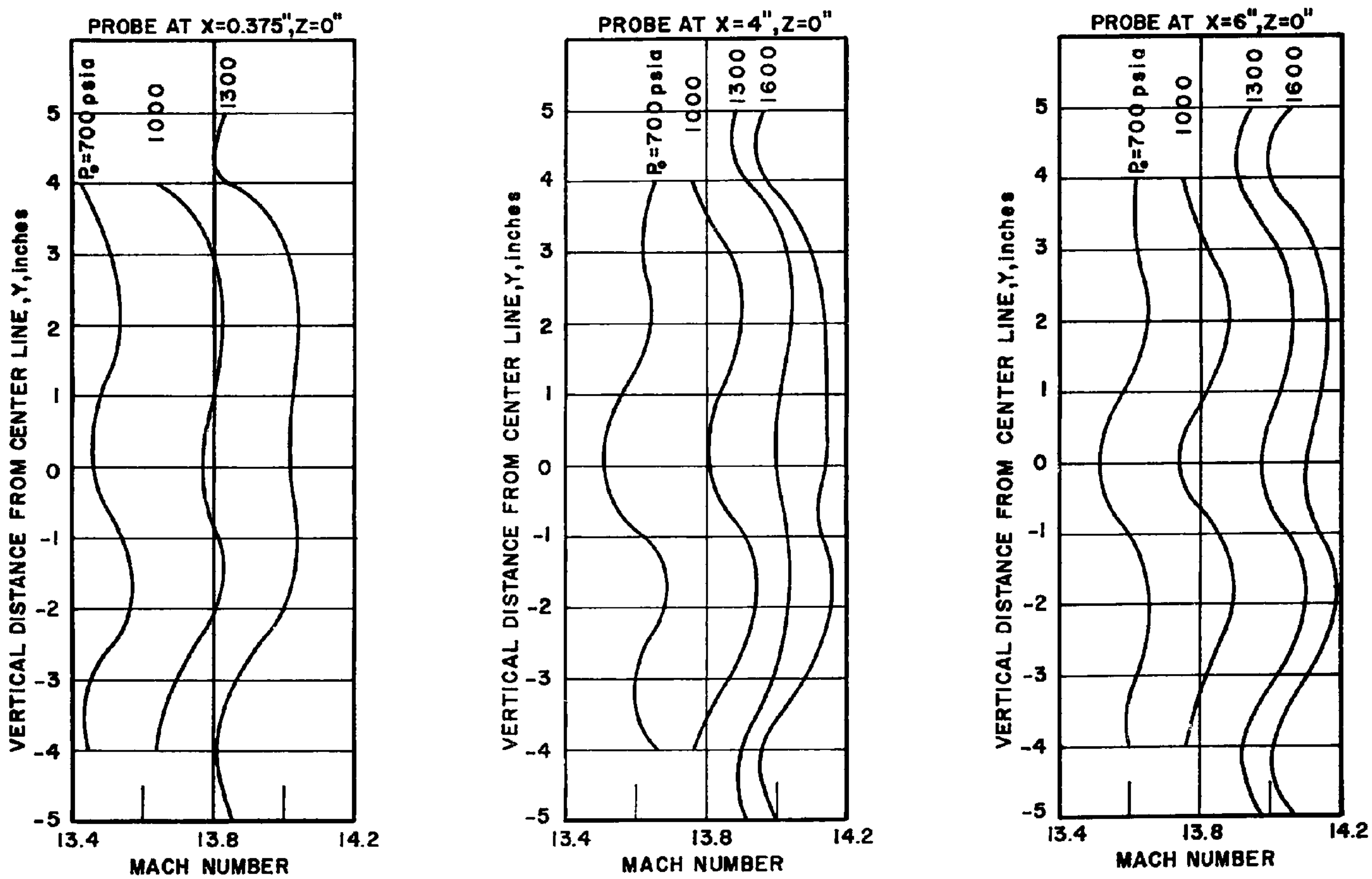


FIGURE 11 -VERTICAL MACH NUMBER DISTRIBUTION OF HTS-14
(THROAT #1; T_0=2260°R)

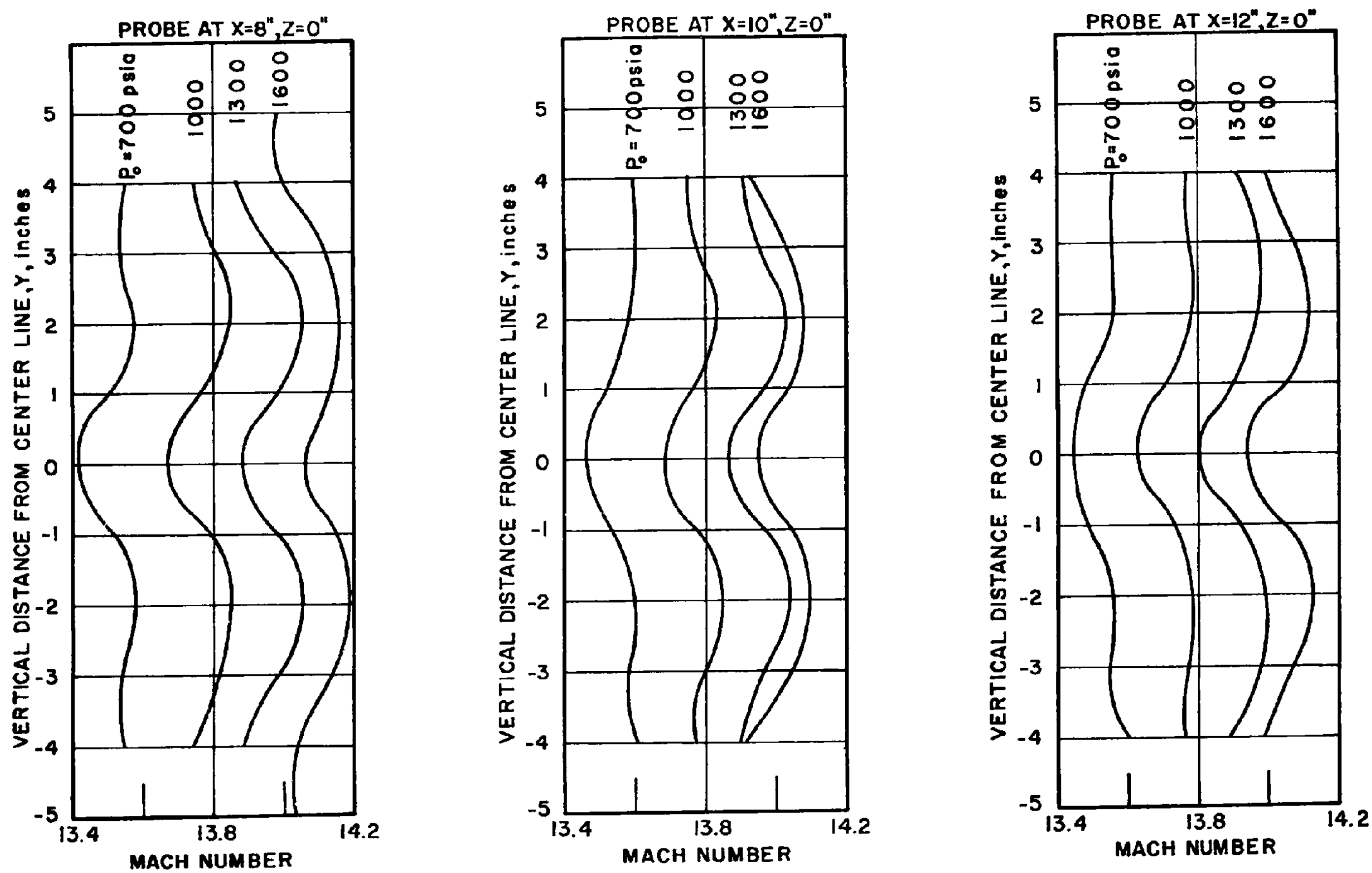


FIGURE 12 -VERTICAL MACH NUMBER DISTRIBUTION OF HTS-14
(THROAT #1; T_0=2260°R)

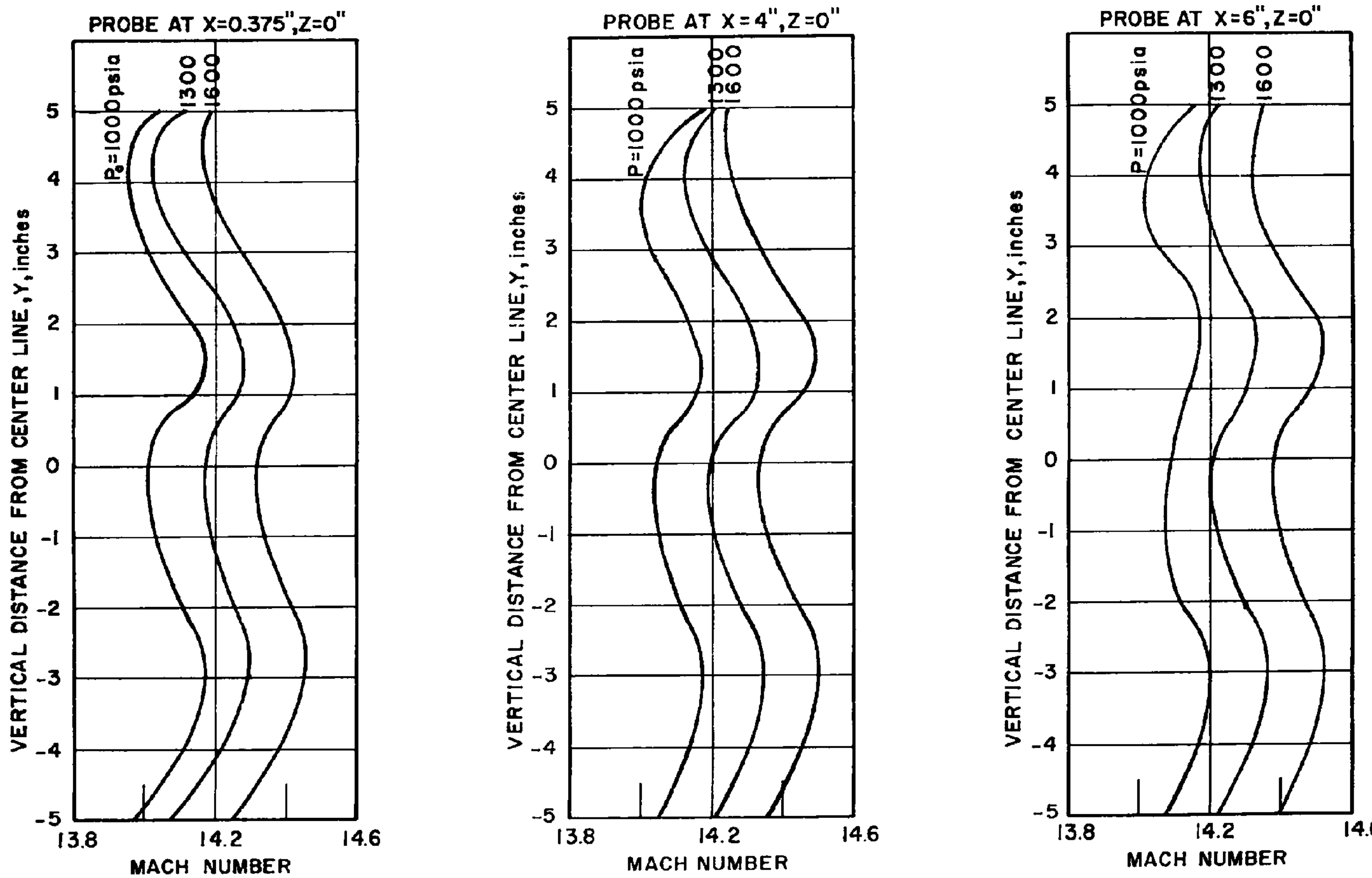


FIGURE 13-VERTICAL MACH NUMBER DISTRIBUTION OF HTS-14
(THROAT # 2 ; T_o=1940°R)

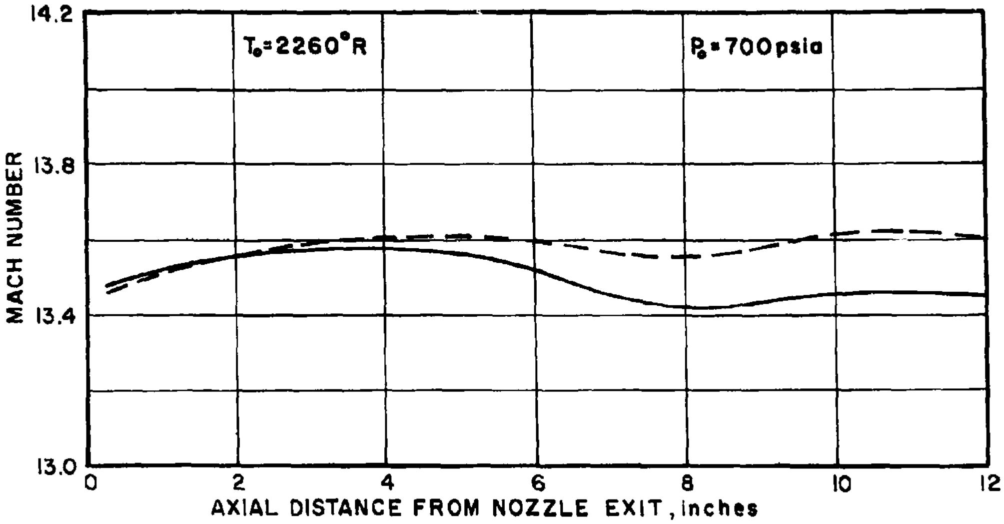
Tables I and II list the maximum Mach number variations in both the vertical and axial directions for both throat sections. As shown, the maximum variation in Mach number in the vertical direction with throat #1 is 1.59%, while with throat #2 the maximum variation is 1.97%. In the axial direction, however, the maximum variation for throat #1 is 1.81%, while for throat #2 it is only 0.57%. These per-cent variations were computed assuming the lower value of Mach number as the correct value, thus yielding the higher possible per-cent error.

Figure 17 illustrates the variation of Mach number with total pressure. As shown, the change in Mach number with total pressure is greater for throat #1 than throat #2. However, it should again be noted that the variation in temperature between the two tests would account for a portion of this variation. Table III presents this data in tabulated form.

TABLE I

Maximum Per-Cent Variation in Mach Number In Vertical Direction

Axial Location, x, inches	Maximum Mach No. Variation, per-cent	
	Throat #1	Throat #2
0.375	1.59	1.97
4.0	1.33	1.97
6.0	1.43	1.61
8.0	1.46	1.96
10.0	1.30	
12.0	1.36	



—— TUNNEL CENTER LINE
– – – 4" RADIUS FROM TUNNEL CENTER LINE

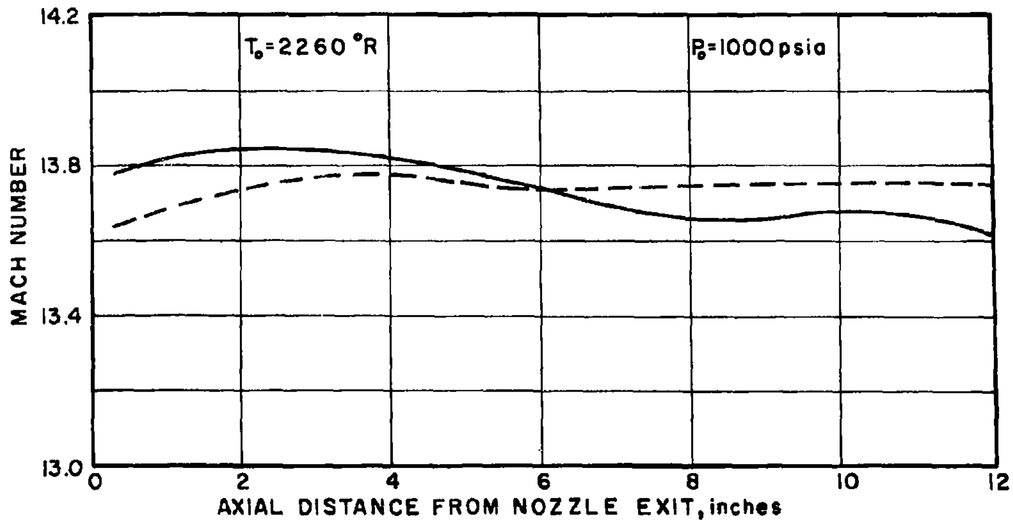


FIGURE 14 -AXIAL MACH NUMBER DISTRIBUTION OF HTS-14 (THROAT #1)

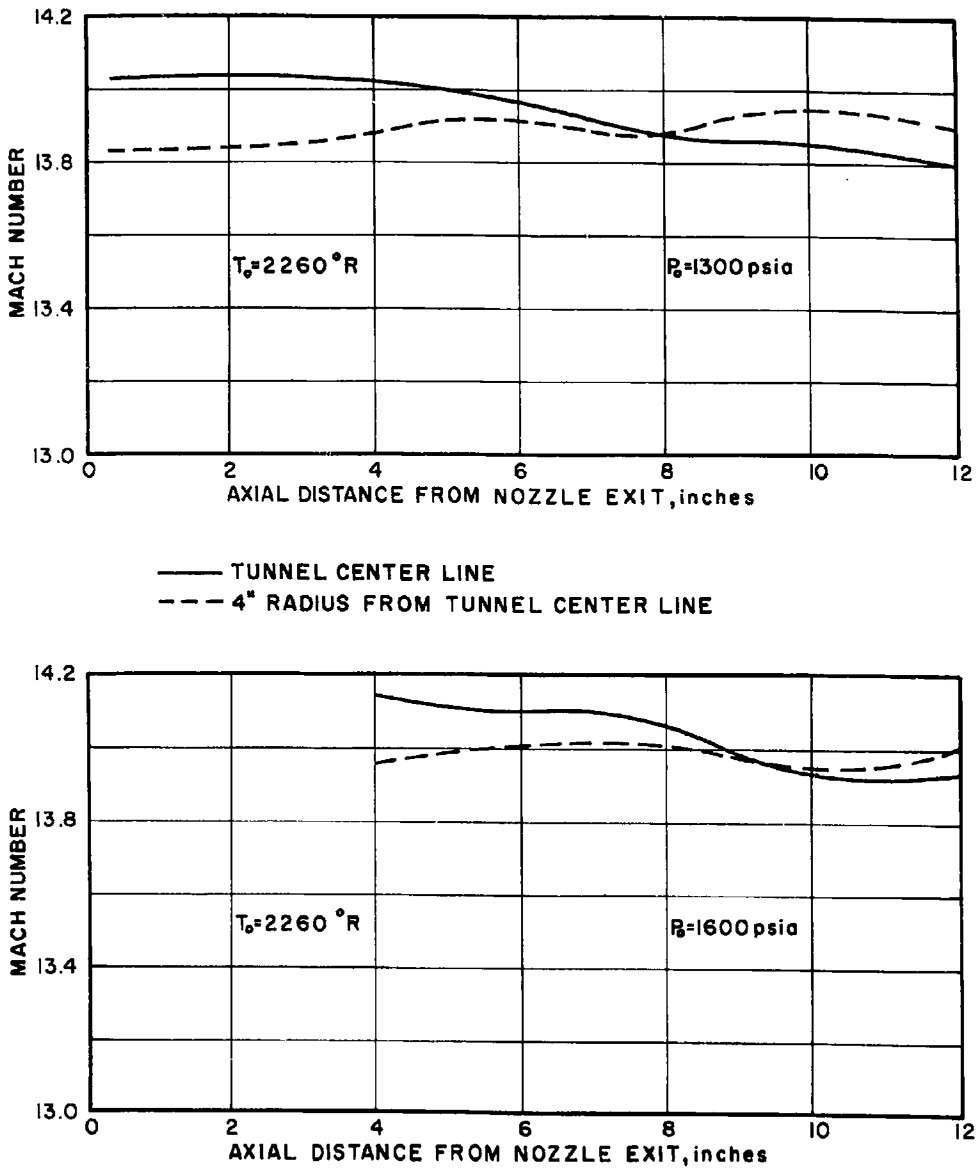


FIGURE 15 -AXIAL MACH NUMBER DISTRIBUTION OF HTS-14 (THROAT #1)

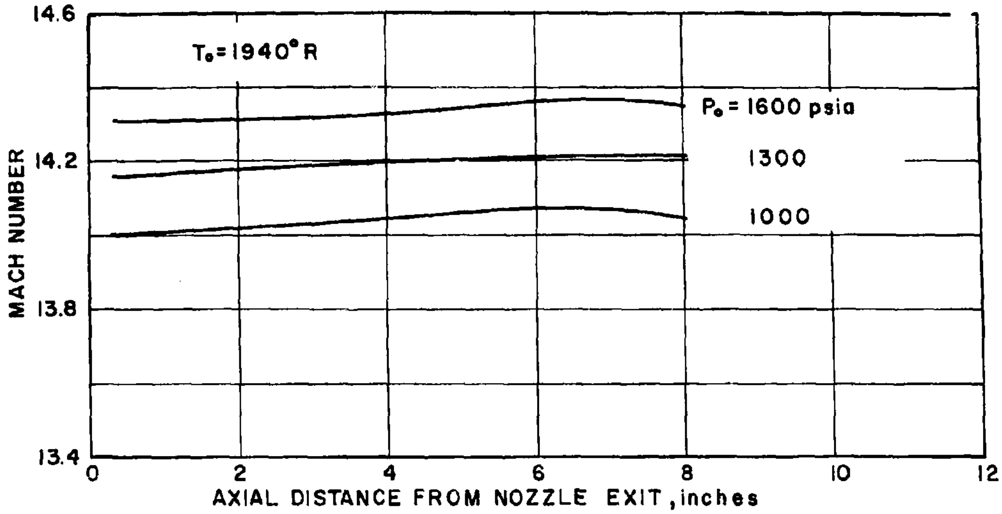


FIGURE 16-AXIAL MACH NUMBER DISTRIBUTION OF HTS-14 (THROAT # 2)

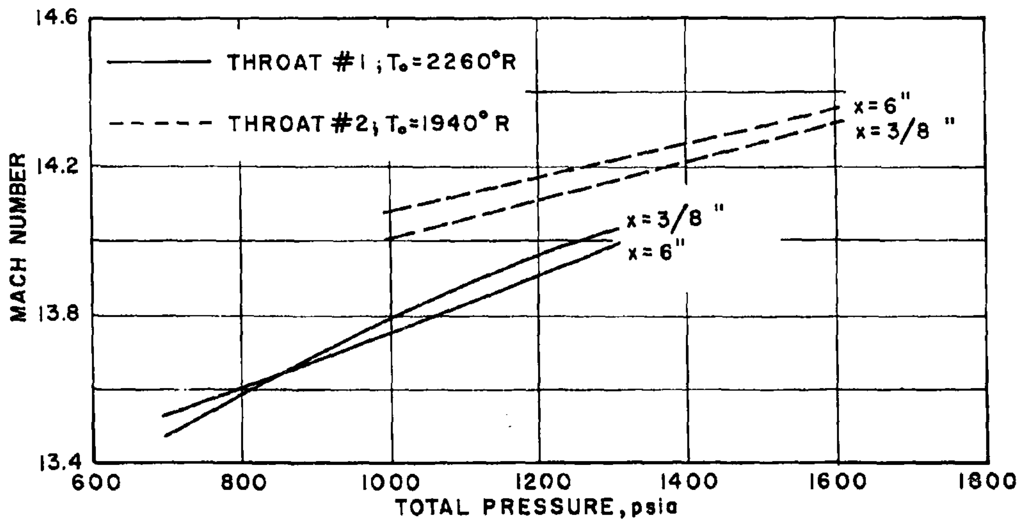


FIGURE 17-VARIATION OF MACH NUMBER WITH TOTAL PRESSURE

TABLE II

Maximum Per-Cent Variation in Mach Number In The Axial Direction

Stagnation Pressure psia	Maximum Mach No. Variation, per-cent		
	Throat #1		Throat #2
	℄	4"Radius From ℄	℄
700	1.19	1.19	
1000	1.69	1.03	0.57
1300	1.81	0.87	0.28
1600	1.51	0.50	0.35

TABLE III

Variation Of Mach Number With Total Pressure

Axial Location x, inches	Total Temperature ^{o}R	% Variation per 100 psia	
		Throat #1	Throat #2
3/8	2260	0.68	
	1940		0.37
6	2260	0.57	
	1940		0.33

TEMPERATURE SURVEY

The total temperature survey performed in the HTS-14 consisted of a vertical traverse on the tunnel's lateral centerline at an axial location 16 1/16 inches downstream from the nozzle exit plane.

The probe used was designed and manufactured by the Rosemont Aeronautical Laboratory in Minneapolis, Minnesota, and has a designation of T-1305-3400-Pt-Pt-13% Rh by the above named manufacturer. The probe utilizes a platinum-platinum-rhodium thermocouple, and was initially calibrated at Mach 10.5. Since the triple shielding was designed for this Mach number, the absolute total temperature at Mach 14 could not be measured, but accurate qualitative data could be obtained. The output of the thermocouple was fed into a Mosley X-Y plotter and was plotted versus the probe's vertical position. Figure 18 shows the results of this test. It may be observed from this plot that the diameter of the thermal core is approximately identical to the diameter of the viscous core.

BLOCKAGE TEST

The primary purpose of the blockage test was to determine the angular blockage limit in the HTS-14 of various size models. The models initially tested were considered to be of a more severe blockage configuration than research models in the design stage; thus, it was expected that the blockage limits of the models tested would be a conservative estimate for the limits of future research models. However, results of these tests indicated that additional tests were needed to accurately predict the blockage limits of various configurations.

Models and Model Support Description

The models initially tested were hemisphere cylinders of 1.90, 2.123, 2.326, 2.513 inch diameter. In later tests a hemisphere cylinder of 0.625 inches was tested, along with a 20° cone with a base diameter of 2.5 inches. This cone is of the same physical dimensions as the two models which will be used to check and extend existing theories on boundary layer-shock wave interaction, wall temperature effects, and inviscid pressure distribution for flow over a cone at small angles of attack.

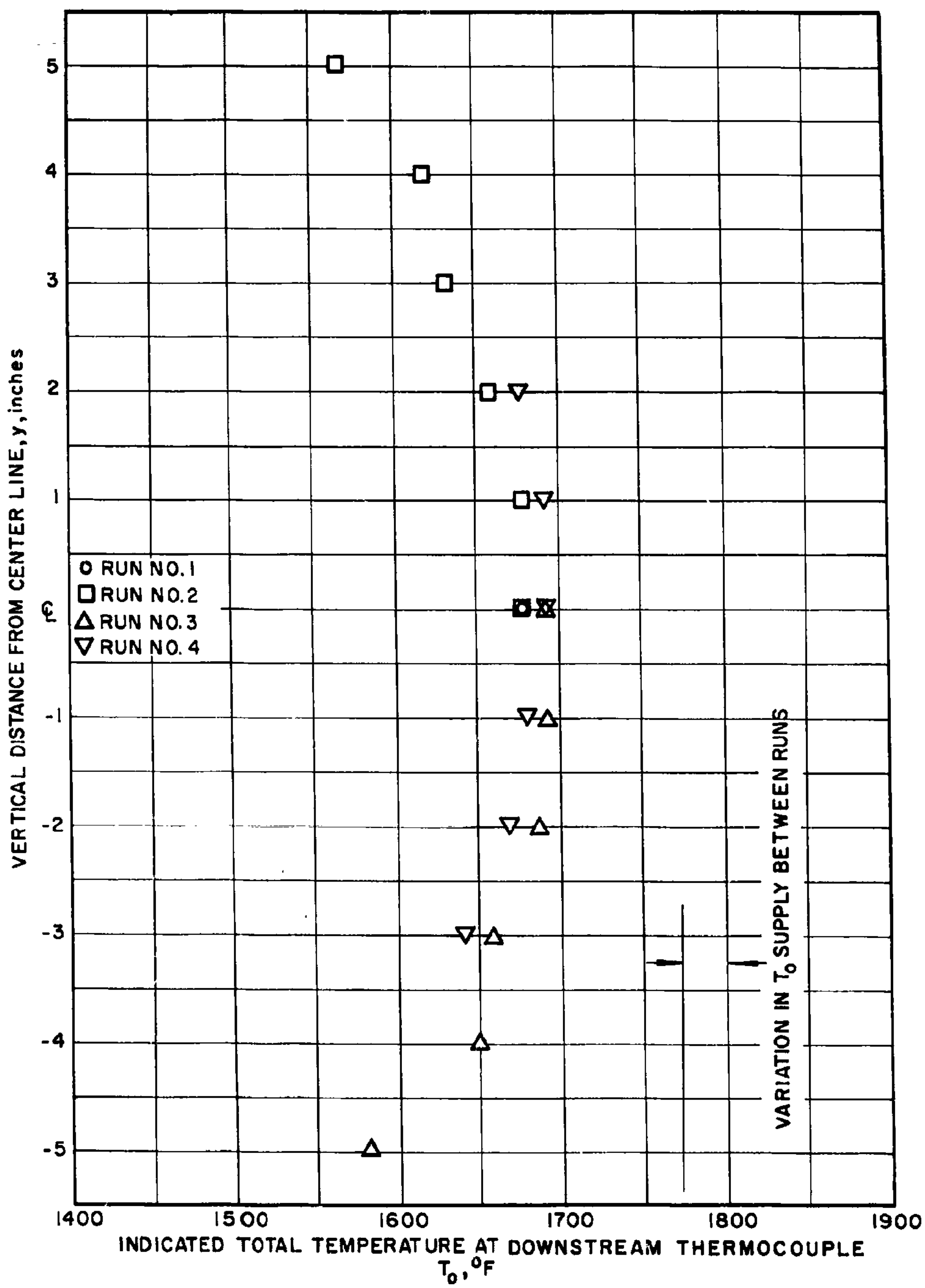


FIGURE 18 -TOTAL TEMPERATURE DISTRIBUTION IN HTS-14
(THROAT #1)

The model support system installed in the HTS-14 has an axial range of 10 inches and can be pitched through angles of attack from +20° to -60°. The center of pitch is located 12½ inches upstream from the model support faceplate. The leading edge of the support strut has a radius of ¼ inch, while the strut itself has a depth of 5 5/8 inches and a maximum thickness of 2 inches. The leading edge is tapered .578 inches per inch for the initial 2 19/32 inches and is inclined at an angle of 117° in a clockwise direction to the free stream flow direction.

For the blockage tests described in this report the center of pitch for the hemisphere cylinder models was the base of the hemisphere portion of the model and for the cone, which was 7 inches long, the center of pitch was its geometric center.

Instrumentation And Test Procedure

The criterion used for determining blockage was the ratio of cabin pressure to free stream static pressure, as it has been observed in other open jet wind tunnels, that when the cabin static pressure increases above 4 to 5 times free stream static pressure the jet is affected.

The free stream static pressure was calculated assuming isentropic expansion from the total conditions, while the cabin static pressure was monitored through a Statham Model P731-TC-350-1 absolute pressure transducer. The output from this transducer was amplified by a Consolidated Engineering Corporation Amplifier System, Model D, and then fed into a Mosely X-Y plotter. The cabin static pressure was plotted along the Y axis while the angle of pitch was recorded along the X axis. Thus, the angle at which blockage occurred could be determined directly from this plot, using the aforementioned criterion.

Results and Conclusions

The results of the blockage tests were somewhat surprising, as they indicated that tunnel blockage was independent of model size and total pressure, as shown in Figure 19. This result indicates that the majority of blockage is due to the model support system and not due to the pitching of the model. In fact, as shown in Figure 19, the blockage actually decreased slightly with increasing model size, thus indicating that the shock wave from the model reduced the total pressure loss across the entire system of shocks set up due to the model and support system.

The variation of tunnel blockage with the axial position of the model was as expected, that is, the closer the model is to the nozzle exit the greater the blockage. This phenomena is illustrated in Figure 19.

The data from the cone model used in the blockage program is shown in Figure 26, and illustrates a higher angle of attack limit for this model than that for the hemisphere cylinder models.

Another point noted with interest during these tests was the manner in which the tunnel went out of flow for positive and negative pitching of the model. At negative angles of attack the tunnel went out of flow by passing a normal shock from the diffuser into the nozzle, while at positive angles of attack spillage over the diffuser caused the cabin static pressure to increase above the allowable limits.

The results obtained during the blockage tests clearly indicate that a general statement regarding tunnel blockage based on model area cannot be made, as it is definitely affected by many factors in addition to frontal area. In addition, it was found that the model support system was a large contributor to the factors which affect blockage. Hence, if models are to be tested at high angles of attack, it is recommended that preliminary tests be conducted with each particular configuration to determine the blockage limits.

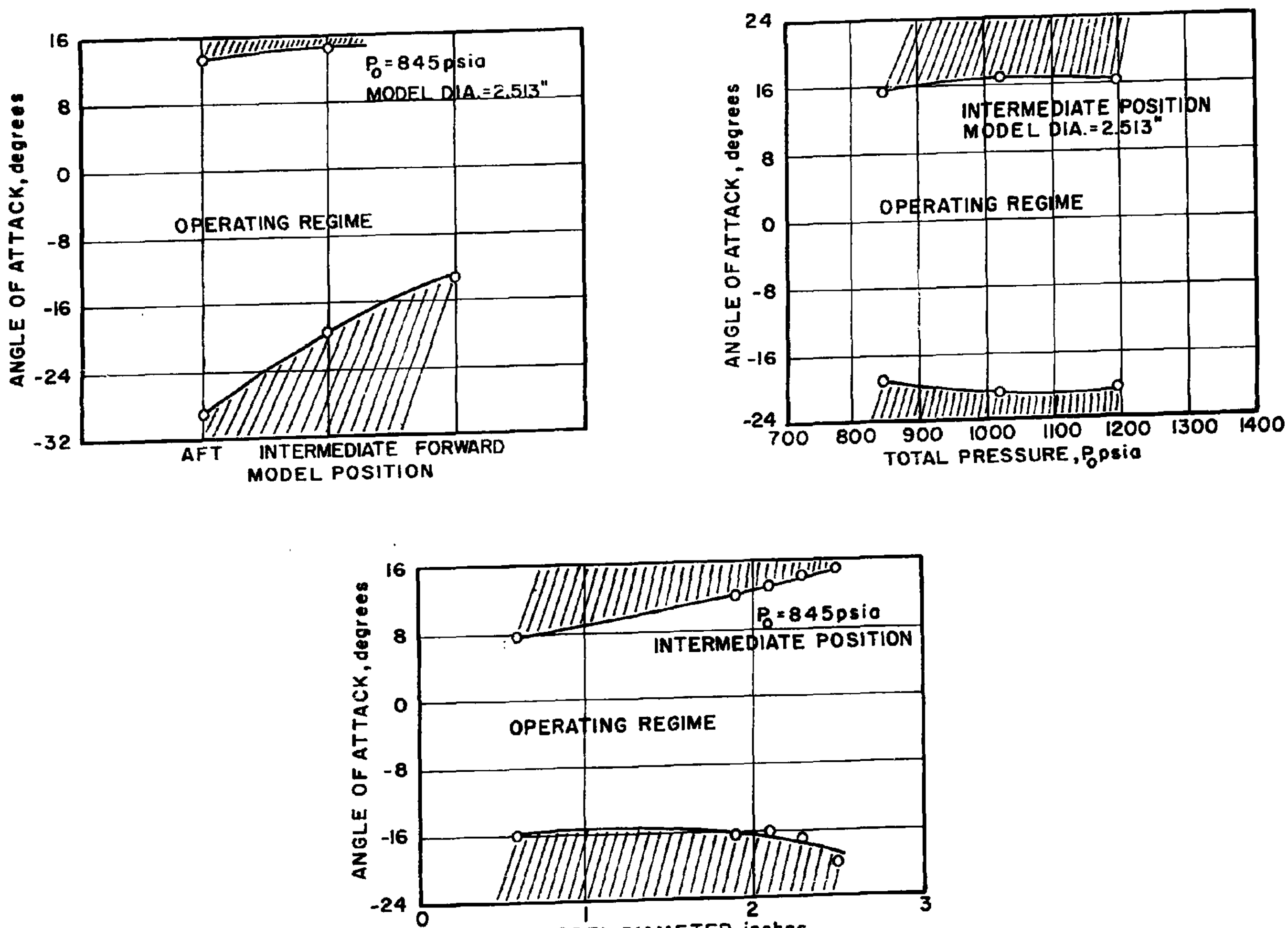


FIGURE 19 – BLOCKAGE LIMITS OF HTS-14 FOR VARIOUS SIZED HEMISPHERE CYLINDER MODELS, TOTAL PRESSURES, AND MODEL POSITIONS

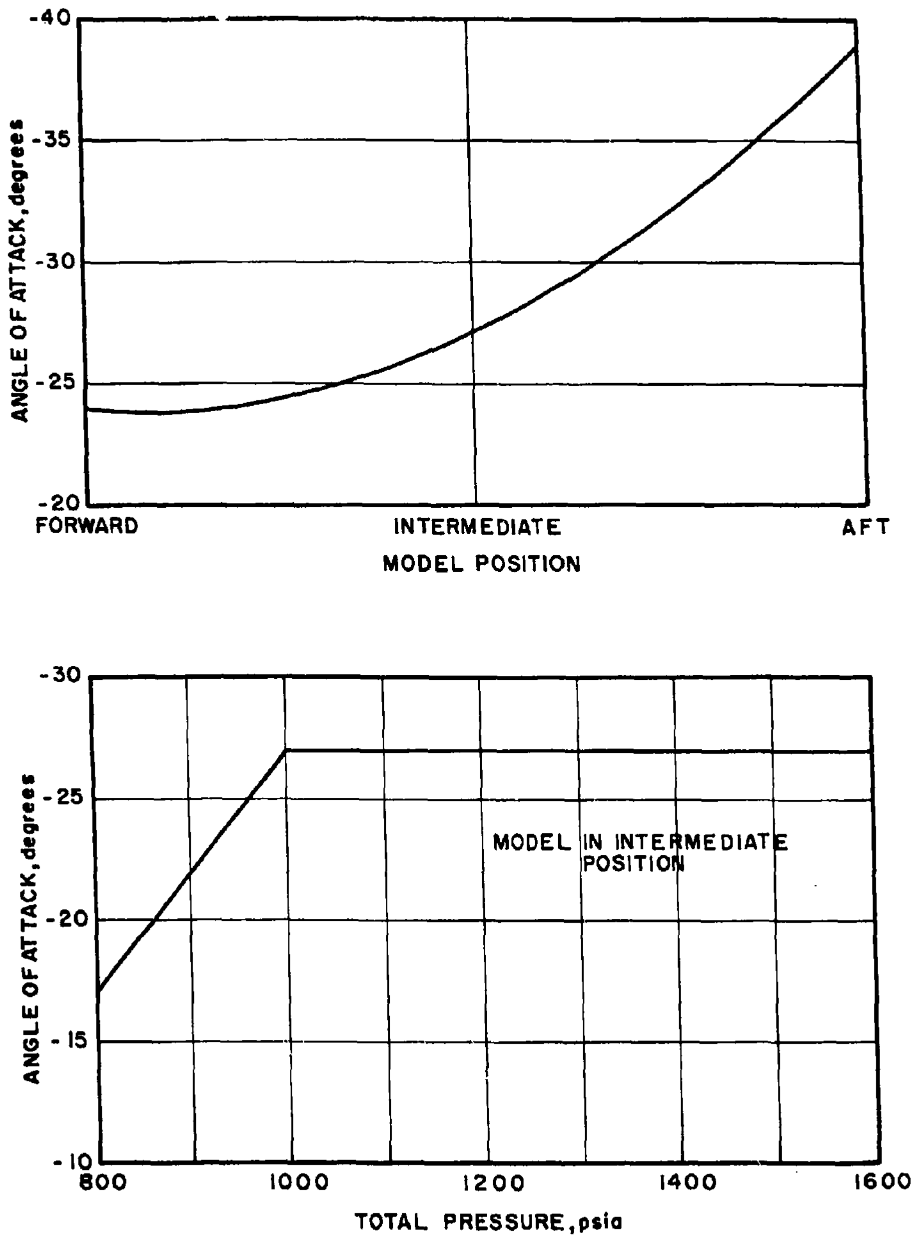


FIGURE 20–BLOCKAGE LIMITS OF HTS-14 FOR CONE MODEL

REFERENCES

1. Gregorek, G. M., and Lee, J. D., "Design Performance and Operational Characteristics of the ARL Twenty-Inch Hypersonic Wind Tunnel", ARL 62-392, August 1962.

2. Gregorek, G. M. "Initial Calibrations and Performance of the ARL Twenty-Inch Hypersonic Wind Tunnel", ARL 62-393, August 1962.

3. Ames Research Staff, "Equations, Tables, and Charts for Compressible Flow", NACA Report 1135, 1953.

4. Daum, F. L., "The Condensation of Air in a Hypersonic Wind Tunnel", ARL 63-42, February 1963.

5. Bromley and Wilke, "Viscosity at Low Temperatures", T. R. HE-150-157, University of California.

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